Optimizing snubber design through frequency-domain analysis

Rayleigh LanAntonio Manenti. - July 11, 2017

The use of a snubber circuit to damp the voltage ringing stemming from parasitic oscillation in switching voltage regulators (VRs) is often not an option. The components for this circuitry must be carefully selected to get the proper attenuation without wasting unnecessary power. This article presents an analytical method based on frequency-domain analysis that leads to simple, yet accurate, equations to determine the optimum value of the components for an RC snubber. Following the step-by-step procedure described in the conclusion, an optimal RC snubber can be designed to obtain the required ringing attenuation.

Introduction

Switching voltage regulators are used nowadays in almost every electronic device, from smartphones to cars. Performance has been pushed to the limit, efficiency has reached the high nineties, and size has shrunk thanks to deep circuit integration. A few decades of research and development has also made voltage regulator design a well-understood topic with tens of different topologies available to satisfy everyone’s needs.

Regardless of the topology adopted, carefully designed placement and layout is crucial for the proper operation of the regulator. Minimizing the parasitic components due to layout is a critical aspect of the design process because of the high-voltage, high-current signals that switch at few hundreds of kHz—or more—on the board. Here, even the smallest parasitic components can cause potentially troublesome oscillations that can create electromagnetic interference (EMI) and, over time, stress the IC. Even if a proper layout is a must to limit the parasitic, sometimes, because of space constraints, mechanical limitations, tight specs or extreme operating conditions, a snubber network is one technique to limit the oscillations created by the remaining parasitic components.

The design of the snubber circuits requires a fine-tuning of all its components since, as explained in the next paragraph, increasing the strength of the snubber reduces the voltage ringing at the expense of converter efficiency. Recommendations provided in most of the traditional application notes on the market take this topic quite lightly, as if converter efficiency was not a key selling point.

Regardless of how much oscillation attenuation is required, most app notes [1], [2], [3] recommend using the following two equations to get the proper parameters:
The recommended values are the same regardless if the application fails the specs by a couple of volts or needs to cut the ringing by 50%. Clearly, this “one-value-fits-all” approach is not optimized and cannot be used to design high-efficiency, best-in-class products.

The analysis proposed in this article focuses on the RC snubber circuit and provides a clear and rigorous way to find the optimal values for its components based on the actual needs. The first section describes the strengths and weaknesses of RC snubbers, along with a rigorous way to measure the parasitic components. The following section describes how the value of the optimum snubber resistor is mathematically derived using the analysis in the frequency domain, leading to a simple—yet rigorous—equation. Next, numerical simulations are used to derive the equation to select the best snubber capacitor. Finally, a few examples and comparison with traditional methods show the strength of the proposed analysis. The conclusion conveys a step-by-step procedure to use this method.

**The RC snubber**

*Figure 1* shows the typical application of an RC snubber circuit applied to a synchronous buck converter. In the ideal application, when the low-side (LS) FET opens and the high-side (HS) FET closes, the voltage on the switching node (Vx) rises from low, slightly below GND due to the LS FET body diode conduction during the dead time, to high, the input voltage.

![RC snubber circuit applied to a synchronous buck converter.](image)

When real-world parasitic components (resistance, inductance, and capacitance) are taken into account, the voltage on the Vx node starts oscillating during the commutation (red curve in *Figure 2*), stressing the device above the design limits and causing EM interference and noise injection in the adjacent circuits.
Figure 2 Effect of the parasitic components on the switching node in a buck converter.

Acting as a load at the proper frequency, the RC snubber network placed on the Vx node damps the oscillation. Its effectiveness—in terms of the amount of ringing reduction—improves with the value of the snubber capacitor (Figure 3), and its upper limit should be determined by the efficiency drop associated with it [4].

Figure 3 Effect of the snubber on the Vx ringing. The higher the snubber capacitance, the stronger the ringing attenuation.

During every switching cycle, Csnb must be charged and discharged, dissipating an average power equal to:

$$P_D = C_{snb} V_{in}^2 f_{sw}$$  \( \text{(3)} \)

The bigger Csnb, the higher the energy that goes into charging and discharging the snubber, reducing the overall VR efficiency.

The circuit in Figure 4 models the parasitic components and the snubber network under the conditions described above.

The HS FET is closed and represented with its RDSon resistance. The LS FET is open instead, and contributes only with its output capacitance. The parasitic inductance is mainly due to the PCB traces, package, and pins.
To summarize the components in Figure 4:

- R1 is the sum of the HS FET RDSon and the trace resistance from the input voltage (the closest input capacitor) to the Vx node;
- L1 is the parasitic inductance introduced by the PCB trace, package, soldering, and pins;
- C1 is dominated by the output capacitance of the HS and LS FETs

![Figure 4](image)

**Figure 4** Model of the electrical circuit including the parasitic components and the snubber circuit.

Given the parasitic nature of these components, and the fact that their value depends on many factors (including PCB, soldering, placement...), their values must be measured and should not be estimated based on datasheets values.

Here’s a simple and accurate method to measure R1, C1, and L1. The Vx voltage of the circuit in Figure 4 (with the exclusion of the snubber components) is described by the following equation:

\[
V_x(t) = V_i(1 - e^{-\alpha t}\cos(\omega_{r1}t + \theta_d))
\]

(4)

Where:

\[
\alpha = \frac{R_1}{2L_1}
\]

(5)

\[
\omega_{r1} = \frac{1}{\sqrt{L_1C_1 - \alpha^2}}
\]

(6)

Adding an additional capacitor of known value—Cadd—in parallel to C1 shifts the angular frequency to a lower value \(\omega_{r2}\).

\[
\omega_{r2} = \frac{1}{\sqrt{L_1(C_1 + C_{add}) - \alpha^2}}
\]

(7)
Figure 5 shows the experiment with Simplis simulations. \( \omega r1 \) and \( \omega r2 \) can be measured from the waveforms as:

\[
\omega_r = \frac{2 \pi}{T_{rx}} \rightarrow \begin{cases} 
\omega_1 = 667 \text{ rad/\mu s} \\
\omega_2 = 298 \text{ rad/\mu s}
\end{cases}
\]  

(8)

\( \alpha \) can be calculated from the first and second peak \( (V_1 \text{ and } V_2) \) as:

\[
\alpha = -\ln \left( \frac{V_r - V_{in}}{V_1 - V_{in}} \right) \left( \frac{1}{T_{rx}} \right) = 2.72 \frac{1}{\mu s}
\]

(9)

And Cadd is a known quantity (6nF in the example) since it was added during the test.

Knowing these values, the above system of three equations with three unknowns can be solved as:

\[
L_1 = \frac{1}{C_{add}} \left( \frac{1}{\omega_r^2 + \alpha^2} - \frac{1}{\omega_{r1}^2 + \alpha^2} \right) = 1.5nH
\]

(10)

\[
C_1 = \frac{1}{(\omega_{r1}^2 + \alpha^2)L_1} = 1.5nF
\]

(11)

\[
R_1 = 2\alpha L_1 = 8m\Omega
\]

(12)

Once the values of these parasitic components are determined, the design of the snubber can start. In this paper, the values of R1, C1 and L1 will be assumed to be the following unless otherwise noted.

R1 = 10m\Omega

C1 = 0.5nF
Choosing the proper Rsnb value

For now, assume that the value of the snubber capacitor Csnb is already known. The method to identify this value will be described in the next paragraph.

By grouping the components shown in Figure 4 and describing them with the Laplace transform, the circuit can be simplified as shown in Figure 6a, where:

\[ Z_1 = R_1 + sL_1 \]  
\[ Z_2 = \frac{1}{sC_1} \]  
\[ Z_{snb} = R_{snb} + \frac{1}{sC_{snb}} \]

Finally, Figure 6b shows the last simplification obtained by calculating the parallel of Z2 and Zsnb:

\[ Z_p = \frac{Z_2 \cdot Z_{snb}}{Z_2 + Z_{snb}} \]

Figure 6: Model of the electrical circuit including the parasitic components and the snubber circuit in the frequency domain

The gain of the circuit, defined as the ratio between the voltage on VX node and the input voltage, can then be calculated for both of the cases, with and without the snubber network.

\[ G_{std}(s) = \frac{V_x}{V_{in}} = \frac{Z_2(s)}{Z_2(s) + Z_1(s)} \]
\[ G_{snb}(s) = \frac{V_x}{V_{in}} = \frac{Z_p(s)}{Z_p(s) + Z_1(s)} \]
Plotting the $|G_{snb}(j\omega)|$ for two extreme values of $R_{snb}$ (**Figure 7**) provides a clear picture of the impact that the value of this component has on the system response.

![Gain vs Frequency](image)

**Figure 7** $|G_{snb}(j\omega)|$ for extreme values of $R_{snb}$.

For $R_{snb} = \infty$, i.e. no snubber, the gain response peaks at the resonant frequency between $L_1$ and $C_1$ ($f_{o1}$), which is about 183MHz considering the standard values mentioned earlier.

$$f_{o1} = \frac{1}{2\pi \sqrt{L_1 \cdot C_1}} \tag{19}$$

On the contrary, replacing $R_{snb}$ with a 0Ω resistor, i.e. making the snubber as strong as possible, pushes the resonant frequency all the way down to $f_{o2} \approx 92$MHz since the snubber capacitor in parallel to $C_1$ increases the overall capacitance.

$$f_{o2} = \frac{1}{2\pi \sqrt{L_1 \cdot (C_1 + C_{snb})}} \tag{20}$$

Evaluating Eq(18) for different values of $R_{snb}$ (**Figure 8**) shows what happens for intermediate values of the snubber resistor. Two are the key concepts. The first is that, while increasing $R_{snb}$, the peak of the black curve slowly decreases until, eventually, it turns into growth of the red peak. The optimal $R_{snb}$ is at the edge of this transition, which provides the lowest overall gain. The second key point is that there is one specific frequency ($f_{o3}$) where all the curves intersect. At $f_{o3}$ the gain is constant regardless of $R_{snb}$ and corresponds to the lowest overall gain when the optimal $R_{snb}$ is adopted.
The information collected so far tells us that there is an optimal snubber resistor that minimizes the overall amplitude of the gain response, but its value is not yet clear. To get to it there are a few other steps to take.

Since the mathematical analysis is quite complex, let’s try to simplify the circuit where possible. The impedance $Z_1$ (Eq. (13)) is dominated by $R_1$ at low frequency, which becomes negligible, compared to the inductor impedance, at high frequency. This means that, for angular frequencies much higher than the frequency of the zero determined by $R_1$ and $L_1$, the impact of $R_1$ is negligible.

As explained in Figure 7, even with the strongest snubber ($R_{snb} = 0\Omega$), the minimum resonant frequency will be $f_{o2}$ (Eq. (20)). By replacing $\omega_{o2}$ in the previous equation, $R_1$ can be ignored for

$$\omega \gg \omega_2 = \frac{R_1}{L_1}$$

$$R_1 \ll \omega \cdot L_1$$

As explained in Figure 7, even with the strongest snubber ($R_{snb} = 0\Omega$), the minimum resonant frequency will be $f_{o2}$ (Eq. (20)). By replacing $\omega_{o2}$ in the previous equation, $R_1$ can be ignored for

$$R_1 \ll \frac{L_1}{\sqrt{L_1 \cdot (C_1 + C_{snb})}} \Rightarrow R_1 \ll \frac{L_1}{\sqrt{C_1 + C_{snb}}}$$

This is the case in most applications requiring a snubber circuit. For example, considering $C_{snb} = 3 \times C_1 = 1.5nF$, $R_1$ can be neglected.
\[ R_1 = 10 \text{m}\Omega \ll 870 \text{m}\Omega \]  

From the approximation, \( G_{\text{snb}}(s) \) from Eq.(18) becomes:

\[
G_{\text{snb}}(s) = \frac{V_x}{V_{in}} = \frac{Z_0(s)}{Z_0(s) + Z_1(s)} = \frac{s \cdot R_{\text{snb}} C_{\text{snb}} + 1}{s^3 \cdot L_1 R_{\text{snb}} C_1 C_{\text{snb}} + s^2 \cdot L_1 (C_1 + C_{\text{snb}}) + s \cdot R_{\text{snb}} C_{\text{snb}} + 1}
\]  

(25)

and then:

\[
|G_{\text{snb}}(j\omega)| = \frac{(\omega R_{\text{snb}} C_{\text{snb}})^2 + 1}{\sqrt{\omega R_{\text{snb}} C_{\text{snb}} \cdot (1 - \omega^2 L_1 C_1)^2 + [1 - \omega^2 L_1 (C_1 + C_{\text{snb}})]^2}}
\]  

(26)

We also know that \( |G_{\text{snb}}(j\omega)| \) at \( \omega_{\text{o3}} \) is constant regardless of \( R_{\text{snb}} \). Which means:

\[
\frac{(\omega_{\text{o3}} R_{\text{snb}} C_{\text{snb}})^2}{[\omega_{\text{o3}} R_{\text{snb}} C_{\text{snb}} \cdot (1 - \omega_{\text{o3}}^2 L_1 C_1)]^2} = \frac{1}{[1 - \omega_{\text{o3}}^2 L_1 (C_1 + C_{\text{snb}})]^2}
\]  

(27)

Solving in \( \omega_{\text{o3}} \):

\[
\omega_{\text{o3}} = \sqrt{\frac{2}{L_1 (2C_1 + C_{\text{snb}})}}
\]  

(28)

Replacing Eq.(28) into Eq.(26) gives:

\[
|G_{\text{snb}}(j\omega_{\text{o3}})| = \frac{2C_1 + C_{\text{snb}}}{C_{\text{snb}}} = G_x
\]  

(29)

The optimum value of \( R_{\text{snb}} \) is the one associated with the \( |G_{\text{snb}}(j\omega)| \) curve whose maximum happens at \( \omega_{\text{o3}} \).

\[
\frac{d|G_{\text{snb}}(j\omega)|}{d\omega} = \frac{d}{d\omega} \frac{(\omega R_{\text{snb}} C_{\text{snb}})^2 + 1}{\sqrt{[\omega R_{\text{snb}} C_{\text{snb}} \cdot (1 - \omega^2 L_1 C_1)]^2 + [1 - \omega^2 L_1 (C_1 + C_{\text{snb}})]^2}} = 0
\]  

(30)

at \( \omega = \omega_{\text{o3}} = \sqrt{\frac{2}{L_1 (2C_1 + C_{\text{snb}})}} \)

After further derivation:

\[
R_{\text{snb opt}} = \sqrt{\frac{L_1 (2C_1 + C_{\text{snb}}) (C_1 + C_{\text{snb}})}{2C_{\text{snb}}^2 C_1}}
\]  

(31)

With \( L_1 = 1.5\text{nH}, C_1 = 0.5\text{nF} \) and \( C_{\text{snb}} = 0.5\text{nF} \) the optimum snubber resistor is:

\[ R_{\text{snb opt}} = 3\Omega \]
The simulation results reported in Figure 9 (conditions in the caption) confirm that using $R_{sb\_opt} = 3\Omega$ provides the lowest overall ringing.

![Graph showing simulation results](image)

**Figure 9** Simulations confirm that $R_{sb\_opt}$ provides the lowest $V_x$ ringing ($R_1 = 10\,\text{m}\Omega$, $L_1 = 1.5\,\text{nH}$, $C_1 = 0.5\,\text{nF}$, $C_{snb} = 0.5\,\text{nF}$).

**Choosing the proper Csnb value**

Choosing the proper Cs\textsubscript{nb} value

As explained in the introduction paragraph, the bigger the snubber capacitance, the smaller the amplitude of the oscillations (Figure 3). At the same time, the energy required to charge and discharge the capacitor increases (Eq.(3)), affecting the efficiency. The optimum value for the capacitor is then the one which provides the right ringing attenuation without wasting any additional power.

One approach to find the optimum value for C\textsubscript{snb} is to follow a rigorous mathematical approach, similar to what was done in the previous paragraph for R\textsubscript{snb}. Solving the equations in the time domain would lead to a third-order differential equation whose solution (finding the first oscillation peak and solving on C\textsubscript{snb}) would be far more complicated.

A different approach, presented in this paper, consists of exploiting the power of numerical computation to solve those equations using Simplis to simulate the circuit in Figure 4 under different conditions. The goal, similar to what was done for R\textsubscript{snb}, provides a simple equation to calculate the optimal value for the snubber capacitor. Let's first define the gain introduced by the snubber and ratio between the maximum voltage with the snubber over the maximum voltage without the snubber. Since the snubber is supposed to reduce the voltage ringing, this number will be smaller than one, hence an attenuation of the ringing.
Note that Eq.(32) is not a function $R_{\text{snb}}$ under the assumption that the optimum value defined by Eq.(31) is used. In simple words, the value of $G_{\text{snb}}$ tells how much ringing voltage is left after adding the snubber. $G_{\text{snb}} = 0.8$, for example, means that the ringing amplitude with the snubber is reduced to 80% of the original value.

The first round of simulations consists in keeping the value of the inductor $L_1$ constant (1.5nH) while varying the value of $C_1$ and its ratio with $C_{\text{snb}}$. The data from these simulations (one subset of which is reported in Figure 10 as reference) is shown in Table 1, where the left side reports the raw data expressed in terms of maximum ringing voltage and the right side reports the attenuation calculated with Eq. (32).

### Table 1 Result of the simulation with $L_1 = 1.5\text{nH}$ and $R_{\text{snb}}_{\text{opt}}.$

<table>
<thead>
<tr>
<th>$V_x$ Peak</th>
<th>$C_1$</th>
<th>$C_{\text{snb}}/C_1$</th>
<th>0.5nF</th>
<th>1nF</th>
<th>5nF</th>
<th>10nF</th>
<th>Gain Eq. (32)</th>
<th>0.5nF</th>
<th>1nF</th>
<th>5nF</th>
<th>10nF</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - No Snb</td>
<td></td>
<td></td>
<td>23.89V</td>
<td>23.85V</td>
<td>23.66V</td>
<td>23.52V</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0.1</td>
<td></td>
<td></td>
<td>23.30V</td>
<td>23.26V</td>
<td>23.07V</td>
<td>22.93V</td>
<td>0.98</td>
<td>0.98</td>
<td>0.97</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>0.2</td>
<td></td>
<td></td>
<td>22.77V</td>
<td>22.73V</td>
<td>22.54V</td>
<td>22.41V</td>
<td>0.95</td>
<td>0.95</td>
<td>0.95</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>0.5</td>
<td></td>
<td></td>
<td>21.50V</td>
<td>21.46V</td>
<td>21.27V</td>
<td>21.14V</td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
<td>0.90</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td>20.01V</td>
<td>19.97V</td>
<td>19.79V</td>
<td>19.66V</td>
<td>0.84</td>
<td>0.84</td>
<td>0.84</td>
<td>0.84</td>
<td>0.83</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>18.20V</td>
<td>18.17V</td>
<td>17.98V</td>
<td>17.85V</td>
<td>0.76</td>
<td>0.76</td>
<td>0.76</td>
<td>0.76</td>
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<tr>
<td>5</td>
<td></td>
<td></td>
<td>15.87V</td>
<td>15.83V</td>
<td>15.65V</td>
<td>15.52V</td>
<td>0.66</td>
<td>0.66</td>
<td>0.66</td>
<td>0.66</td>
<td>0.65</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>14.51V</td>
<td>14.47V</td>
<td>14.29V</td>
<td>14.16V</td>
<td>0.61</td>
<td>0.60</td>
<td>0.60</td>
<td>0.60</td>
<td>0.59</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td>13.59V</td>
<td>13.55V</td>
<td>13.37V</td>
<td>13.24V</td>
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<td>0.56</td>
<td>0.56</td>
<td>0.55</td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
<td>12.92V</td>
<td>12.88V</td>
<td>12.70V</td>
<td>12.58V</td>
<td>0.54</td>
<td>0.54</td>
<td>0.53</td>
<td>0.53</td>
<td>0.53</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td></td>
<td>12.67V</td>
<td>12.63V</td>
<td>12.46V</td>
<td>12.33V</td>
<td>0.53</td>
<td>0.53</td>
<td>0.52</td>
<td>0.52</td>
<td>0.52</td>
</tr>
</tbody>
</table>
Figure 10 Increasing Csnb reduces the oscillation. (C1 = 0.5nF, L1 = 1.5nH, Rsnb_opt)

Plotting this data as a function of Csnb/C1 (Figure 11) brings to light the fact that the attenuation is quite independent from the value of C1 itself and can be simplified as:

$$G_{snb} = F \left( L1, \frac{C_{snb}}{C_1} \right)$$  \hspace{1cm} (33)
The next step is intended to determine how the value of $L_1$ affects this curve. Using a similar approach, $C_1$ is kept constant (0.5nF) and $L_1$ is varied. Interestingly, the results reported in **Figure 12** show how $L_1$ also does not significantly affect the amount of the gain.

![Figure 12: Effect of the $C_{snb}/C_1$ ratio on the $Att_{snb}$ ($C_1$ = constant)](image)

$$G_{snb} = \mathcal{F}\left(\frac{C_{snb}}{C_1}\right)$$  \hspace{1cm} (34)

The only step that is left to take now is to express this curve with an equation. To do this, let’s first focus on $C_{snb}/C_1 \leq 5$. This is the most interesting region for the snubber design. Using a snubber capacitor so much bigger than $C_1$ would certainly cause a big efficiency drop, and indicates that the layout or the choice of the components need to be reviewed.

A reasonable starting point to get the attenuation equation (34) is to use Eq.(29), which describes the gain of the circuit at $\omega_{03}$. From **Figure 12**, we know:
Figure 13 shows how well Eq. (38) tracks the simulation data.

Finally:

\[
\frac{C_{\text{snb}}}{C_1} > \frac{4 - 4 \cdot G_{\text{snb}}}{2 \cdot G_{\text{snb}} - 1} \quad \Rightarrow \quad C_{\text{snb}} > C_1 \cdot \frac{4 - 4 \cdot G_{\text{snb}}}{2 \cdot G_{\text{snb}} - 1}
\]

**Evaluation of the results**

This final paragraph presents a comparison between the method proposed in this paper and those recommended in traditional application notes. As reference, the circuit in Figure 14 will be used to run simulations with Simplis 8.0. Unless otherwise noted, these are the setup conditions:

\(V_{\text{in}} = 12V, R_1 = 10\, \text{m}\Omega, L_1 = 1.5\, \text{nH}, C_1 = 0.5\, \text{nF}, F_{\text{sw}} = 500\, \text{kHz}, V_{X_{\text{NOSNB}}} = 23.72V\)
Three examples will be provided to show the strength of the proposed method in different conditions.

In the first example, the goal is to keep the ringing voltage below 17V. The oscillation reduction required by the snubber is quite strong.

Traditional application notes provide a single set of parameters regardless of the required ringing attenuation. The values, obtained from Eq.(1) and Eq.(2), depend on the parasitic components only (R1, L1, C1). For this reason, these values will not change across the three different examples proposed hereafter.

\[ R_{\text{snb,AN}} = 1.73\Omega, \quad C_{\text{snb,AN}} = 0.5nF \]  \hspace{1cm} (40)

With this set of values, the Simplis simulation shows a maximum Vx voltage of Vx_{\text{MAX,AN}} = 20.1V. Even though an attenuation is achieved, the specs are not met.

Let’s see what happens with the method proposed in this paper, which consists of three main steps.

1. Calculate the required gain from Eq.(32). \( G_{\text{snb}} = 0.717 \), i.e. the snubber needs to reduce the Vx peak to 71.7% of the existing Vx peak level.
2. Calculate Csnb with Eq.(39). In this case, Csnb > 1.3nF. Let’s use Csnb = 1.5nF for this example.
3. Finally, knowing Csnb, use Eq.(31) to calculate the optimum Rsnb = 1.82Ω

Simplis simulation using these values show a maximum peak voltage of 16.9V, which meets the requested specs.

The simulation for this first example is shown in Figure 15. While the values provided using the traditional way don’t satisfy the project requirements, the method explained in this article provides just the optimum values to obtain the right attenuation.
In the second example, the target spec is $V_x \leq 19.8V$. Following the same three steps described above, we get $C_{snb} = 0.5nF$ and $R_{snb} = 3\Omega$ that, according to simulations, attenuate the ringing value to a maximum of 19.8V (right on spec) compared to the same 20.1V guaranteed by traditional approaches. This example highlights the importance of the proper selection for $R_{snb}$. In both cases, in fact, the value of $C_{snb}$ is the same ($C_{snb} = 0.5nF$). Having a way to calculate the optimum snubber resistor makes a difference between passing or failing the specs using the same $C_{snb}$, i.e. the same efficiency drop.

Finally, in the last example, the required reduction is even smaller with $V_x \leq 21V$. Again, the three steps mentioned previously lead to $C_{snb} = 0.3nF$ and $R_{snb} = 4.16\Omega$ with a maximum ringing value of 21V. In this case, both methods lead to solutions that meet the specs. Once again, though, the new method provides a better solution guaranteeing the right voltage level with a lower $C_{snb}$, which, in turn, means lower loss and better overall efficiency.

All of this data is summarized in Table 2.

**Table 2** Summary of example 1. Snubber values recommended by online app notes don’t meet the design target. Those obtained with the approach presented in this paper do.

<table>
<thead>
<tr>
<th></th>
<th>Proposed Method in this article</th>
<th>Traditional Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Eq.(31) &amp; Eq.(40)</td>
<td>Eq.(1) &amp; Eq.(2)</td>
</tr>
<tr>
<td>$V_x_{max \text{ w/o snubber}}$</td>
<td>23.72V</td>
<td>23.72V</td>
</tr>
<tr>
<td>$V_x_{max \text{ spec}}$</td>
<td>21V</td>
<td>19.8V</td>
</tr>
<tr>
<td>$C_{snb}$</td>
<td>0.3nF</td>
<td>0.5nF</td>
</tr>
<tr>
<td>$R_{snb}$</td>
<td>4.16\Omega</td>
<td>3\Omega</td>
</tr>
</tbody>
</table>

**Figure 15** Simulation of the first two examples
Conclusions

This paper presented a new method to choose the snubber values $R_{snb}$ and $C_{snb}$. $R_{snb}$ is calculated using Eq.(31), which was derived through rigorous frequency-domain analysis. $C_{snb}$, instead, is determined using Eq.(39), which was obtained from numerical analysis.

The steps to determine the optimum values of the snubber are summarized here:

- Determine how much gain the snubber must introduce using Eq.(32).

$$G_{snb} = \frac{V_{x_{peak_{SNB}}}}{V_{x_{peak_{noSNB}}}}$$ \hspace{1cm} Eq.(32)

- Measure the parasitic components

<table>
<thead>
<tr>
<th>$L_1$</th>
<th>$C_{add} = \frac{1}{\omega^2_{L_2} + \alpha^2} - \frac{1}{\omega^2_{L_1} + \alpha^2}$</th>
<th>Eq.(10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>$\frac{1}{(\omega^2_{L_1} + \alpha^2)L_1}$</td>
<td>Eq.(11)</td>
</tr>
<tr>
<td>$R_1$</td>
<td>$2\alpha L_1$</td>
<td>Eq.(12)</td>
</tr>
</tbody>
</table>

- Calculate the value of $C_{snb}$ with Eq.(39). Use Eq.(31) to determine the optimum value for $R_{snb}$.

$$C_{snb} > C_1 \cdot \frac{4 - 4 \cdot G_{snb}}{2 \cdot G_{snb} - 1}$$ \hspace{1cm} Eq.(39)

$$R_{snb, opt} = \frac{L_1(2C_1 + C_{snb})(C_1 + C_{snb})}{2\alpha^2 C_{snb} C_1}$$ \hspace{1cm} Eq.(31)

The last paragraph presents a result comparison between the traditional method and the one proposed in this paper to determine the snubber values. It shows how the latter provides a better tuned circuit that always leads to a solution that meets the design specification with overall lower power dissipation.